Ge on Si Photonics Platform for Mid-Infrared Sensors

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***Abstract*—Mid-infrared spectroscopy in the fingerprint region of the electromagnetic spectrum is demonstrated using a Ge on Si photonic platform technology. Components that can be integrated into complete lab-on-a-chip sensors for spectroscopic identification of healthcare and security analytes is presented capable of parts per billion sensitivity.**

***Index Terms*—mid-infrared, Si photonics, sensors, spectroscopy**

The mid-infrared part of the electromagnetic spectrum is where many molecules have strong vibrational and rotational absorptions [1]. Fourier Transform Infrared Spectroscopy (FTIR) is the gold standard for mid-infrared spectroscopy and in many countries is the main technique used by authorities for identifying pollutants, narcotics, explosives, chemical or biological weapons. The technique is also ideal for identifying healthcare analytes that can be used for disease diagnosis. FITRs, however, are expensive and require significant expertise to be used for analytical applications.

There is strong interest in developing chip-scale mid-infrared sensors where analytes can be readily measured and absorption features used to provide unique identification. This is most readily achieved in the fingerprint region of the electromagnetic spectrum (6.7 μm and 20 μm) where the energy of the absorption feature is related to the mass of different atoms attached to the vibration modes being measured. The specificity of detection is therefore far higher in this fingerprint region compared to shorter wavelength measurements [1].

We have proposed Ge on Si as a platform for building complete mid-infrared sensors when combined with III-V quantum cascade lasers (QCLs) as the light source [2]–[10]. Ge is a silicon foundry compatible material which is transparent with losses below 2 dB/cm from 1.8 μm up to 14.5 μm wavelength before lattice absorptions become significant. We have demonstrated waveguides with losses below 5 dB/cm from 7.5 to 11 μm wavelengths and analysis suggests losses $\leq$1 dB/cm can be achieved from 5 μm to 14.5 μm [2]. We have demonstrated quantum well intersubband detectors [3] and microbolometer detectors [4] at these wavelengths. We have used metallically doped n-Ge as a plasmonic absorber with the microbolometers and to concentrate electric fields for improved sensing [5] and demonstrated wide bandwidth polarization rotators [6]. We have also demonstrated ps plasmonic switching [7] and used this for third harmonic generation allowing frequency conversion at mid-infrared wavelengths [8]. Sensing using subsets of these components has been demonstrated with measurements on a range of analytes including organic and inorganic compounds [10] and chemical weapons [5].

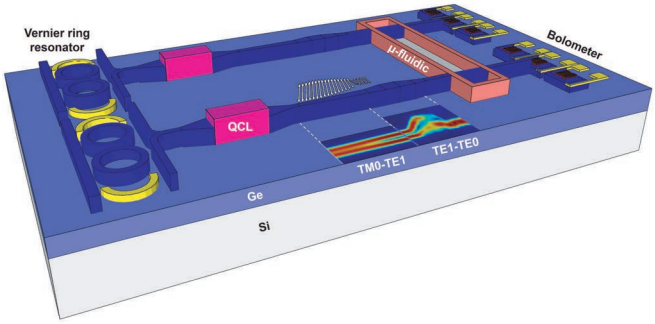

Fig. 1. A schematic diagram of a lab-on-a-chip mid-infrared sensor using QCL sources tuned using Vernier microring resonators with microfluidic control of analytes and microbolometer detection.

The overall system for a lab-on-chip mid-infrared sensor we propose is shown in Fig. 1. III-V QCLs are combined with Vernier microring resonators to provide tunable sources with potentially up to 3 μm bandwidth. Polarization rotators [6] take the TM mode from the QCLs and rotate them to TE which increases the modal overlap with analytes [10] for improved signal to noise. Microfluidics can control the analytes and the interaction lengths with Ge on Si waveguides [10] as the sensing element to maximise dynamic range and microbolometer detectors [4] allow the absorption as a function of the wavelength to be measured.

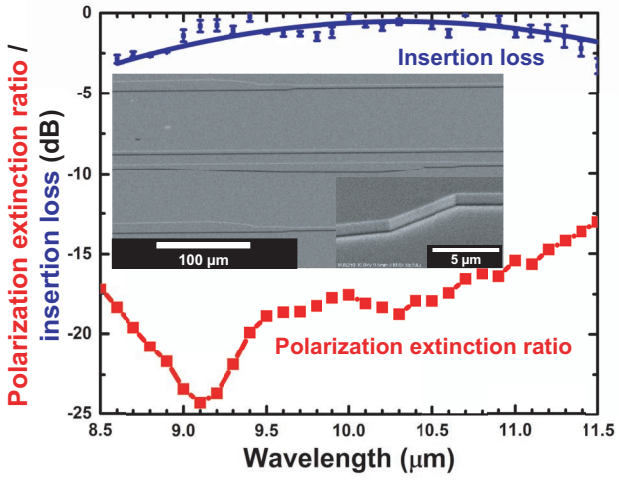

Fig. 2. The insertion loss (blue) and the polarisation extinction ratio (red) as a function of the wavelength for the polarizing rotator. The insert provides two SEM images of the fabricated device.

As an example of a key component for waveguide detection, III-V mid-infrared QCLs at present only provide TM output but the optimum modal overlap for absorption in the waveguides is TE. Therefore to maximise the signal to noise for the measurement of molecular absorptions a polarization rotator is required. A tapered device is presented in Fig. 2 with the experimental results between 8.5 and 11.5 μm wavelength [9] and a scanning electron microscope (SEM) image of the device. This design has a large tolerance to fabrication inaccuracies and provides $\geq$15 dB extinction ratio over a 2 μm bandwidth between 9 and 11 μm wavelengths [9]. As the operating wavelength can be changed from the lateral feature dimensions, and mid-infrared QCLs with 3 μm operating bandwidth are now available, a range of different operating wavelengths can be designed on a single chip offering broadband measurements across 5 to 15 μm wavelengths. This range covers the majority of useful absorption modes for healthcare, security and environmental applications.

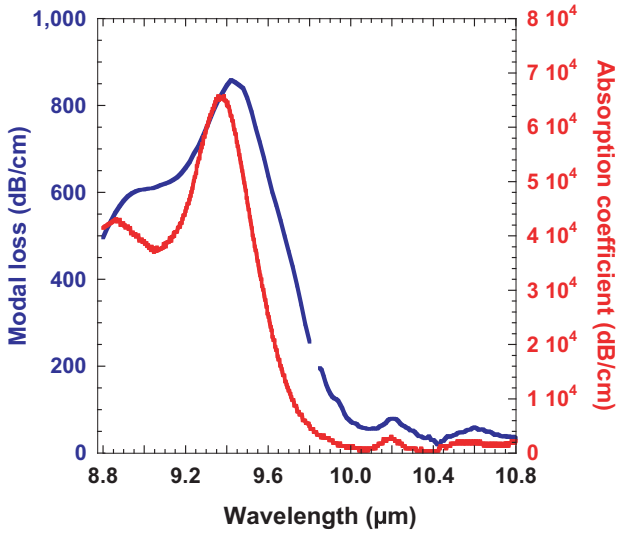

Fig. 3. A comparison of FTIR measurements of HSQ (red) versus waveguide transmission measurements using a 3 μm wide and 100 μm (left) and 1 mm (right) long Ge waveguides (blue).

The FTIR measured spectra of annealed hydrogen silsesquioxane (HSQ) for 120 s at 350°C compared to electron irradiated and unannealed HSQ on Ge waveguides are shown in Fig. 2. The absorption peaks between 8.8 to 9.8 μm are related to Si-O-Si vibration modes [10]. As the HSQ is irradiated or annealed, it changes from a cage to network like structure and the absorption peaks red-shifts. One of the issues with short anneals is that not all the HSQ may get to the same temperature resulting in a variety of molecular structures. This is clearly observed as the peak around 9.4 μm are at different wavelengths for the FTIR and Ge waveguide measurements due to different processing conditions. The Ge waveguides probe the HSQ closest to the waveguide whilst the FTIR measurement provides an average probe throughout the film thickness. Also the 1 mm long Ge waveguide demonstrates a number of additional features not observed in the FTIR measurements between 10.0 and 10.8 μm assigned to the formation of $H_2SiO_{2/2}$ from $HSiO_{3/2}$ thereby providing better signal to noise resolution of these absorptions. This demonstrates that multiple waveguide lengths can optimise the dynamic range for each set of absorptions to provide the maximum resolution whilst FTIR or a single wavelength length may only be optimised for a few absorptions. Improved dynamic range is a significant advantage of the waveguide approach over FTIR and especially important for high specificity of analytes requiring identification from both strong and weak absorption modes.

As an example of sensitivity, breath analysis for the diagnosis of chronic kidney disease requires detection of ammonia in concentrations of 400 parts per billion (ppb) [10]. Assuming 4 μm wide waveguides with 1 dB/cm loss for the ammonia absorption at 9.545 μm (absorption cross section 2.78×10^{-18} cm^2) with a modal overlap of 1.2% would require a detector with noise equivalent power of 4×10^{-9} W $Hz^{-\frac{1}{2}}$, a 50 mW source and a 100 ms integration time for a signal to noise ratio of 3 to detect 400 ppb [10].

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